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# Functional and Qualification Testing of the InflateSail Technology Demonstrator

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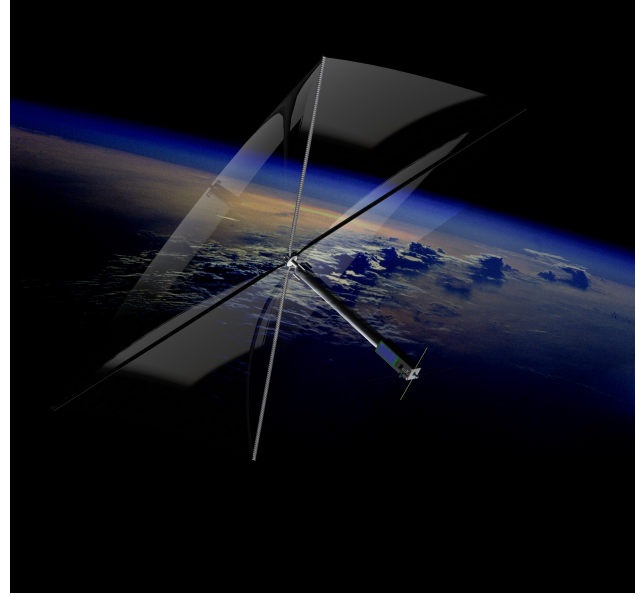
**InflateSail is a 3U CubeSat with 2U dedicated to an experimental drag deorbiting system. The deployable sail has an area of  $10\text{m}^2$  and sits atop a 1m long inflatable rigidizable mast. InflateSail is scheduled for launch in 2016 as a technology demonstrator satellite of the QB50 mission. This paper describes the payload functional and qualification tests.**

## I. Introduction

InflateSail is a technology demonstration mission for a drag deorbiting system. Two gossamer structures are deployed from a 3U CubeSat: a 1 m long inflatable-rigidisable mast, and a  $10\text{ m}^2$  drag sail supported by bistable CFRP deployable booms; see Figure 1. The InflateSail satellite will be launched as part of the European QB50 mission in 2016.

The objectives of the InflateSail mission are to verify the functionality of the deployable structures on board, and to illustrate the potential of the sail-mast system as an end-of-life deorbiting solution for larger satellites. The deployable sail would increase a host satellite's aerodynamic drag, thus reducing its orbital decay time. The inflatable mast provides an offset between the centre-of-mass of the host satellite and the centre-of-pressure of the gossamer sail, which facilitates passive attitude stabilisation and thereby maximises the presented drag area.<sup>1</sup> Additionally, InflateSail will demonstrate the use of an aluminium-polymer laminate inflatable cylinder as a lightweight deployable structural member, and use a Cool Gas Generator (CGG) for storage and release of the inflation gas.

This paper describes the InflateSail payloads, and focuses on the functional and qualification testing performed to ensure the gossamer payloads will survive launch, and will deploy successfully in space.

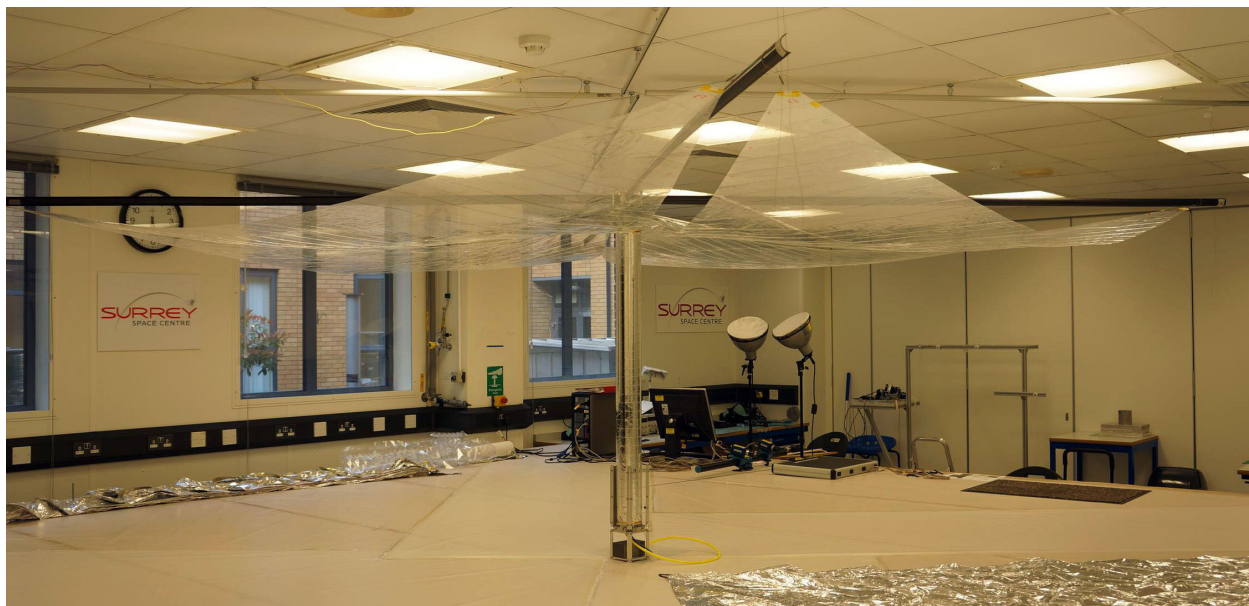


**Figure 1. InflateSail deploys two structures from a 3U CubeSat: a 1 m long inflatable mast, and a  $10\text{ m}^2$  drag augmentation sail supported by four CFRP booms.**

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**Figure 2.** Deployed full-scale Engineering Model of InflateSail. The carbon fibre booms are supported at their tips by a sliding gantry, while the remaining mass (*i.e.* the sail deployment mechanism) is supported by the rigidized inflatable mast.

## II. Satellite and Mission Design

The avionics used in InflateSail are primarily commercial off-the-shelf (COTS) CubeSat components, with the exception of a custom interface board to control the inflation of the deployable mast and deployment of the sail. The external structure is a modified version of a COTS 3U CubeSat chassis. The custom-built payload comprises two deployable systems: an inflatable-rigidisable mast, and a deployable gossamer sail.

### A. Inflatable-Rigidisable Mast

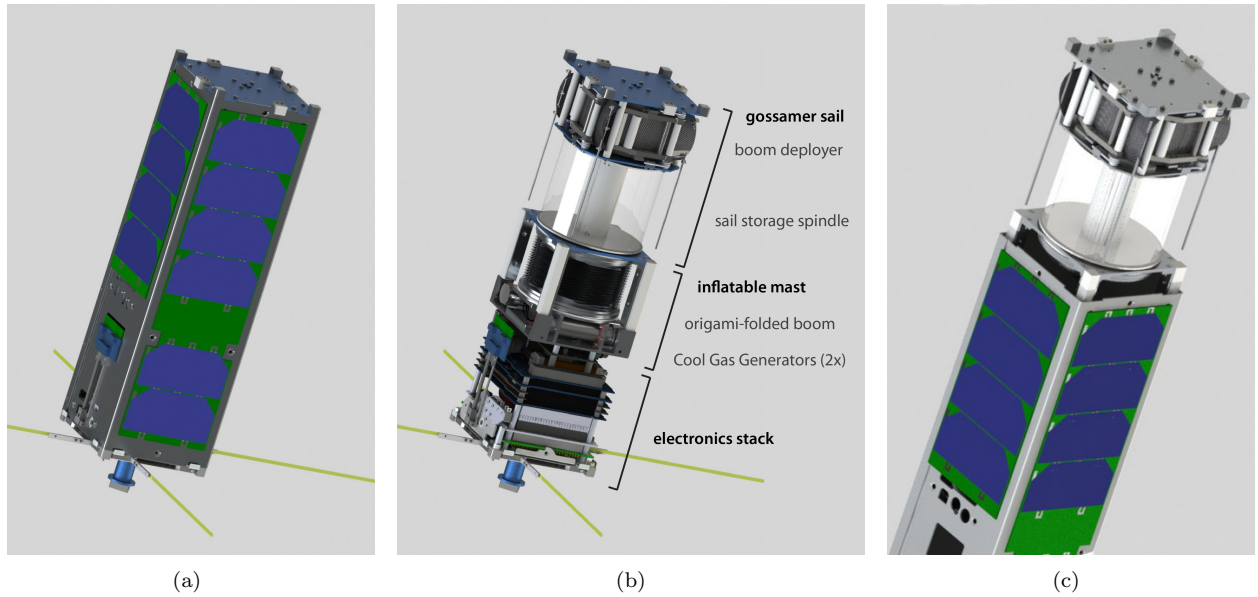
In its deployed configuration the inflatable mast assumes a length of 1 m and diameter of 90 mm, and for launch it is folded down to a height of 63 mm using an origami pattern.<sup>2,3</sup> The skin material consists of an aluminium-polymer laminate, which is strain-rigidised after deployment to remove the creases. A thin Mylar-C bladder improves airtightness, and wiring for the sail deployment motor is stored internally.

The Cool Gas Generator (CGG) inflation system was custom-developed for this mission by TNO and CGG Safety and Systems.<sup>4</sup> Two CGGs, each containing 3.9 grams of nitrogen gas, are installed immediately below the folded cylinder; see Figure 3(b). A single CGG is sufficient to perform the inflatable deployment and rigidisation, with the second included for redundancy.

The initial stages of the inflatable deployment are shown in Figure 3(c). The mast and sail payload is deployed following a “Jack-in-the-box” approach: after activation of the CGG, the released inflation gas pushes open the top of the satellite structure, before the 1 m inflatable extends to its full length. To ensure a smooth deployment from the satellite, the top fitting of the inflatable mast is equipped with four PTFE sliders which run along the inside of the structure. The residual creases in the membrane are removed through plastic deformation of the aluminium-laminate material<sup>2,5</sup> and shortly after deployment the inflation gas is vented in a symmetric pattern outside the spacecraft.

### B. Gossamer Sail

Once the inflatable has been deployed and rigidised, a motor located in the sail storage shaft is used to drive the uncoiling of four bistable CFRP booms from the sail deployment mechanism.<sup>6,7</sup> The four co-wrapped quadrants of a 12  $\mu\text{m}$  thick PEN sail membrane unfurl as the booms extend. The deployed 10  $\text{m}^2$  sail increases the satellite aerodynamic drag, resulting in an accelerated deorbiting time. The inflatable mast



**Figure 3. InflateSail in (a) the stowed configuration, (b) walls and solar panels removed to reveal the internal structure, and (c) in partially deployed configuration, where the sail deployment module is pushed out of the structure by the inflation of the cylindrical mast.**

provides a passive attitude stabilisation, by virtue of the offset between centre-of-mass of the satellite and centre-of-pressure of the sail, ensuring that a maximum drag area is presented by the sail during deorbiting.<sup>1</sup>

### C. Concept of Operations

The mission concept of operations is as follows:

1. commissioning and de-tumbling;
2. inflate and rigidize mast, and confirm deployment;
3. deploy sail, and confirm deployment;
4. deorbit satellite and track altitude using NORAD Two-Line Elements (TLE) and on-board GPS data.

InflateSail is expected to be placed in a  $380 \times 700$  km elliptical orbit. After deployment of the deorbiting sail, the time to demise is predicted to be between 5 and 20 days. Deployment of the inflatable mast and deployable sail will be confirmed through an image captured with an on-board camera.

## III. Functional Testing

The mission payloads (inflatable-rigidisable mast, cool gas generators, and gossamer sail) were functionally tested on component level before being integrated into the Qualification Model. A number of functional tests were performed to verify the functionality of the subsystems.

### A. Inflatable Mast

A complication in the functional testing of the inflatable mast is the single-use nature of the aluminium-polymer skin material: once the structure has been deployed, it cannot be repackaged for subsequent deployments. The system reliability is therefore verified through a series of successful deployments.



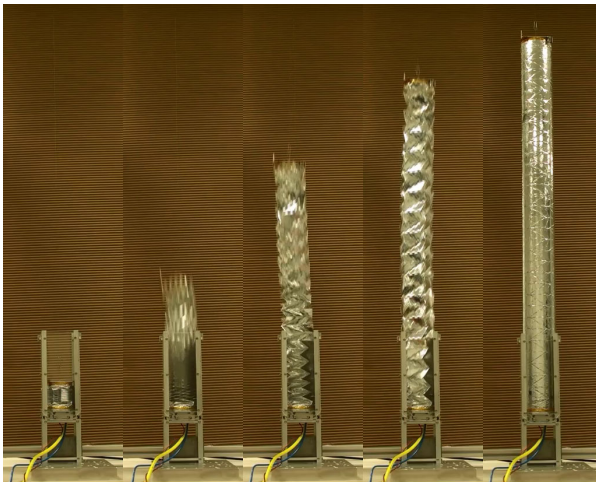
## 1. Mechanical Characterisation

In order to ensure structural performance of the deployed inflatable mast, its stiffness and strength was determined experimentally.<sup>2</sup> Tensile tests on the laminate material had revealed unexpectedly low elastic moduli, which was attributed to non-flatness of the thin specimens (the three-layer laminate is less than  $50\text{ }\mu\text{m}$  thick). Residual creases from the folding process further reduce the effective stiffness of the deployed boom.<sup>8</sup> The efficacy of strain-rigidisation in recovering the stiffness of the inflated mast was investigated by measuring its natural frequency for varying inflation pressures.<sup>2</sup> It was found that the stiffness increases with inflation pressure up to the point of rigidisation (50-55 kPa), after which the stiffness levels off as the cylinder surface smoothens out — see Figure 4.

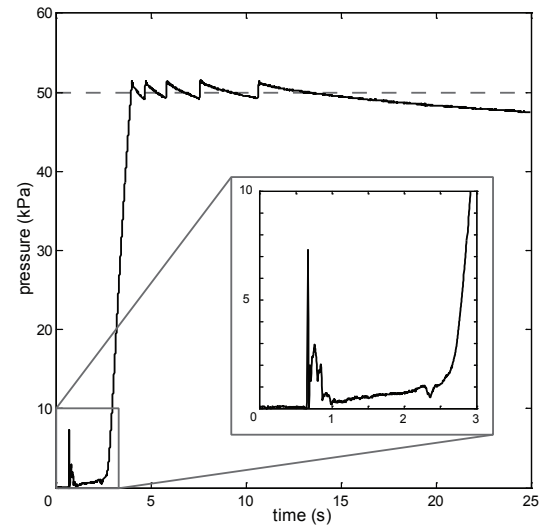
## 2. Ambient Deployment

A series of ambient deployment tests was performed on the inflatable mast. The inflation was done using compressed air, and was pressure-controlled to 50 kPa via a solenoid valve on the air inlet. The weight of the top boom fitting was compensated by running a string over pulleys to a counterweight. All boom deployments have been successful; see Figure 5.

The deployment and rigidisation takes approximately 2–5 seconds, depending on gas inlet pressure. When the inflation gas is released, the internal pressure spikes until the top fitting exits the CubeSat structure, before dropping off during deployment and rapidly ramping up again when the boom is fully extended and the rigidisation pressure of 50 kPa is reached. After full extension, a slight pressure drop can be observed due to leaking of the inflatable; the leakage rates drop off rapidly, and this is not considered to be a concern for in-orbit deployment.



(a)



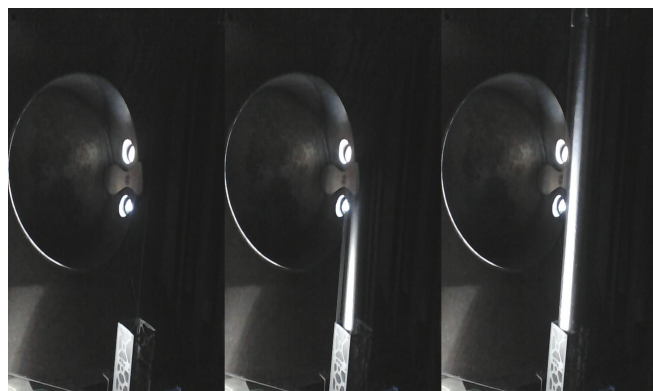
(b)

**Figure 5. Deployment tests of the inflatable: (a) snapshots at different stages of deployment, (b) pressure trace during deployment and rigidisation; the inset shows the pressure during the deployment phase.**

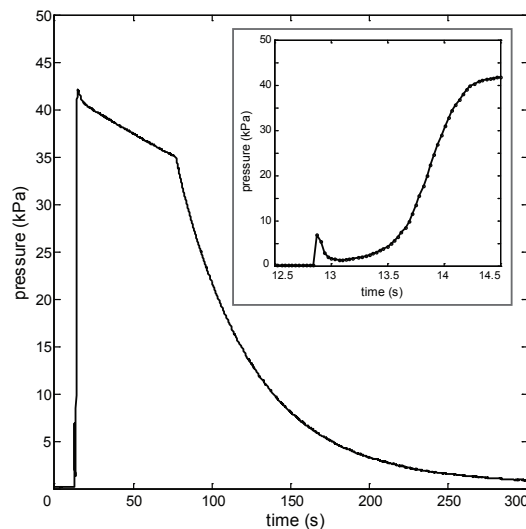
### 3. Vacuum Deployment

A full-scale deployment test was done under vacuum conditions, using a Cool Gas Generator for inflation. The ‘Daedalus’ vacuum chamber at the Surrey Space Centre was able to accommodate the vertical deployment of the inflatable mast (without the sail deployment module). Feedthroughs into the vacuum chamber provided power to activate the solenoid valve inside the inflatable and trigger the CGG gas release, and data lines enabled pressure logging inside the inflatable and a video recording of the deployment.

The deployment was unexpectedly rapid, with full extension reached within 0.5 second and maximum pressure under 2 seconds; see Figure 6. The initial pressure peak is characteristic of the top fitting gathering inertia before the boom begins to expand, causing a momentary drop in pressure. The maximum pressure reached was around 42 kPa, which suggests 3.12 g of nitrogen was released into the inflatable (80% of CGG capacity).



(a)



(b)

**Figure 6. Deployment of inflatable mast inside vacuum chamber, (a) snapshots of deployed configuration, (b) inflation pressure trace during and after deployment; the kink in the depressurisation curve indicates the point where the release valve was opened; the inset shows pressure during deployment and rigidisation phase.**

After deployment, the gas leakage rate was characterised for approximately one minute before the release valve was opened and the inflation gas was vented into the vacuum chamber. Repressurisation of the vacuum chamber resulted in radial buckling of the thin-walled cylinder, as the internal boom pressure could not equalise sufficiently quickly.

### 4. Thermal Extremes

The in-orbit inflation is expected to be performed when the satellite is approximately at ‘room temperature’ and the inflation gas and mast dimensions have been sized accordingly. Further considerations are the glass-transition temperature of the adhesive in the laminate, and shear strength of the transfer tape used to seal the cylinder at higher temperatures. The inflatable mast was therefore not deployed at temperature extremes.

Tests were performed to assess the survivability of the laminate material at high/low temperature conditions. Sections of rigidised boom were placed inside a temperature chamber and taken to  $+150^{\circ}\text{C}$  and  $-70^{\circ}\text{C}$  and inspected visually. After cooling to  $-70^{\circ}\text{C}$  the chamber was opened to subject the material to a rapid temperature shock. No anomalies were observed with the laminate material; see Figure 7.

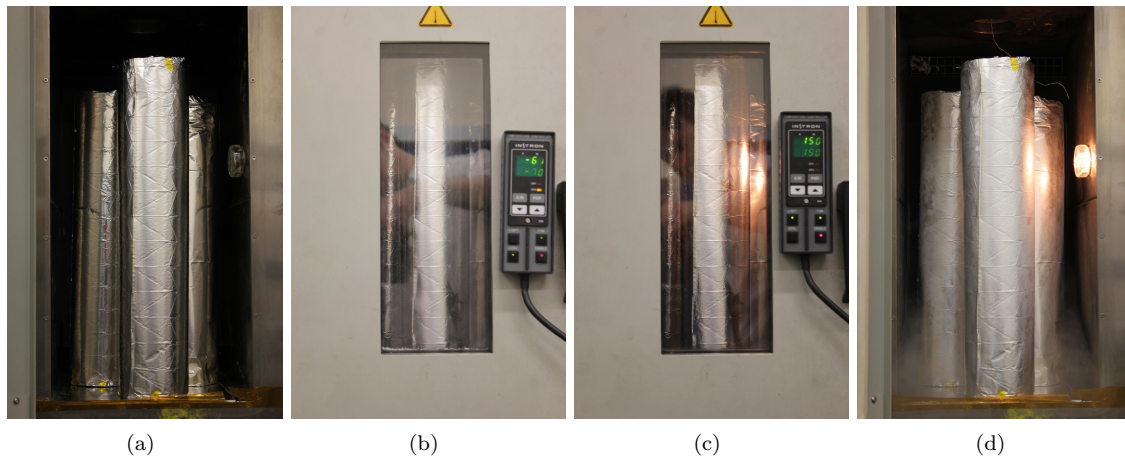


Figure 7. Post-rigidised cylinders were (a) placed in a thermal chamber and taken to temperature extremes of (b)  $-70^{\circ}\text{C}$  and (c)  $+150^{\circ}\text{C}$ ; (d) after cooling to minimum temperature the chamber was opened to simulate rapid change in temperature.

## B. Cool Gas Generator

The Cool Gas Generators (CGGs) were designed in parallel with the inflatable mast. After freezing the design requirements in the summer of 2013, the design was finalized in early 2014, and by May 2014 all parts had been produced and procured, and the test campaign was started.

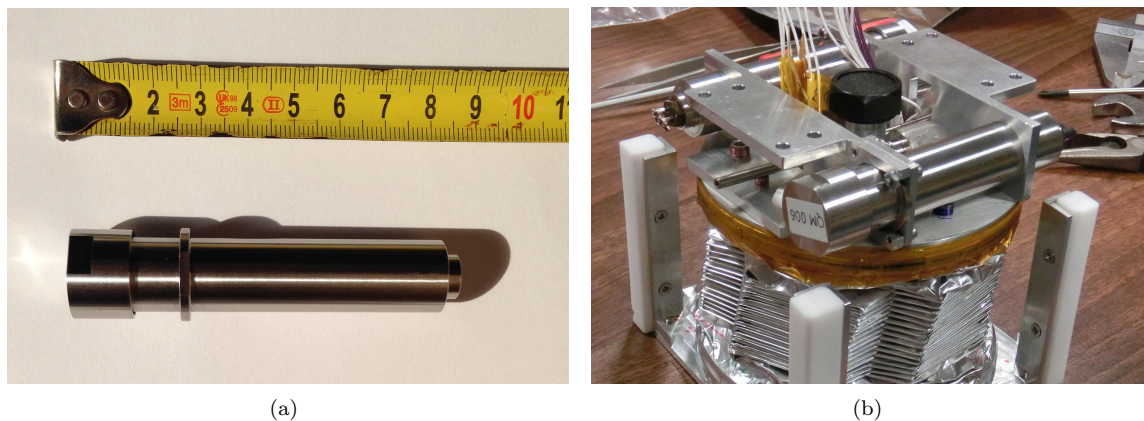


Figure 8. A Qualification Model CGG, (a) fully assembled, and (b) integrated into the InflateSail QM.

For the tests two CGG models were used, a re-usable Demonstration Model (DM) which was equipped with instrumentation ports, and the single-use Qualification Models, meant for qualification and flight. The DM and QM tests were combined in a single test campaign: after test results with the DM were considered to be satisfactory, one QM was tested for verification. The test campaign was conducted in four parts:

1. **Engineering tests of the foil and breaker assembly.** During these tests the rupturing of the foil that isolates the CGG grain from the environment was verified.
2. **Physical properties, pressure and leak tests of the casings.** During these tests all CGG parts were weighed and measured for the correct sizes. The assembled units, without propellant, were tested for pressure resistance and leakage. A new O-ring design was implemented, and the tests were completed successfully. The CGGs were then sent to TNO, where the propellant grain and igniter were added.
3. **Firing test at TNO.** At TNO six tests were conducted with the DM hardware. In the first test a

problem with the ignition was discovered, and traced back to improper mounting of the igniter and grain. This was successfully corrected, and in all subsequent tests reliable ignition was achieved. In some tests, however, the grain did not react completely and thus not all the gas was released. This problem was analysed and is now corrected. One test was conducted at a high temperature (40 °C) and one at a low temperature (0 °C). In both cases reliable ignition was achieved. For the last test a QM was fired inside the transport container, leading to a classification of the CGG outside the hazardous class, which lowers the requirements on transportation of the CGGs significantly.

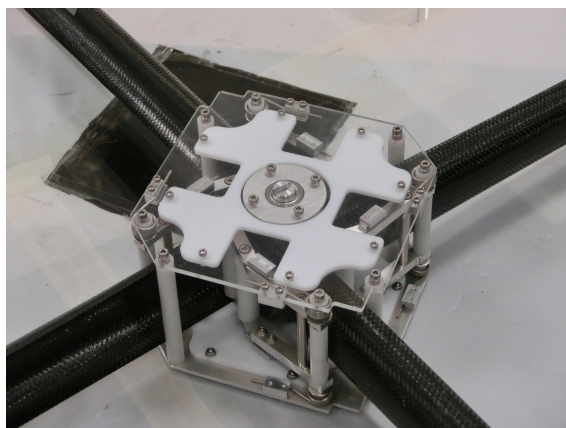
4. **Integration in InflateSail Qualification Model.** One of the QM CGGs was fired in the vacuum deployment test of the inflatable mast, and the second was ignited after the vibration and thermal cycling tests on the InflateSail Qualification Model; see Section IV.

## C. Sail Deployment Tests

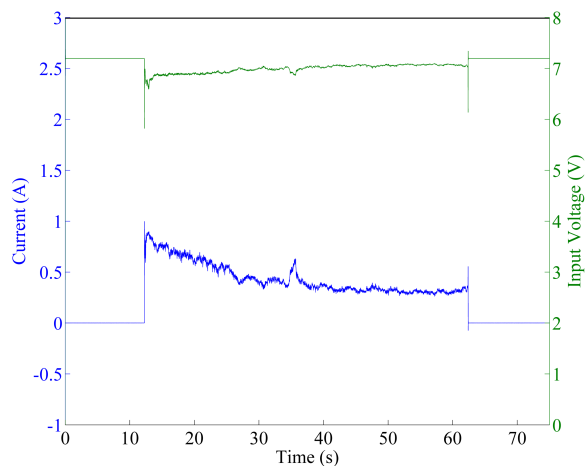
The sail deployment module consists of two components: the boom deployment system, which stores and deploys the four co-coiled CFRP booms, and the sail storage spindle, around which the four sail quadrants are wrapped. The system is an updated version of a previously qualified design,<sup>7,9</sup> with as notable improvements a low-friction sail deployment spindle to reduce deployment loads on the booms, and a smaller boom coil to mitigate blossoming.

### 1. Ambient Deployment

A series of boom deployment tests was performed to verify the performance of the deployment module, fine-tune the custom brushless-DC motor controller and determine the number of motor revolutions required for full sail deployment. In the functional tests a PMMA (Perspex) top plate was used to observe the behaviour of the coiled booms during deployment, and the motor current was measured.



(a)



(b)

**Figure 9. Boom deployment module: (a) a PMMA top plate enabled inspection of the boom coil during deployment, and (b) motor current measured during one of the deployments (6V brushless-DC motor, running at approximately battery voltage of the COTS EPS used in InflateSail, with maximum 60% duty cycle).**

The full-scale sail deployment tests were done on a dedicated deployment table, which is covered in an anti-static film to minimize friction and static attraction on the sail membrane. Although some slippage between coil layers could be seen, no blossoming of the coil was observed under the deployment loads,<sup>7</sup> resulting in a reliable and predictable boom deployment. The sail quadrants are wrapped in the same direction as the deployable booms, and unfurl gradually as the booms extend. The sail is not pulled taut after full deployment of the booms and is therefore expected to billow under the aerodynamic drag.



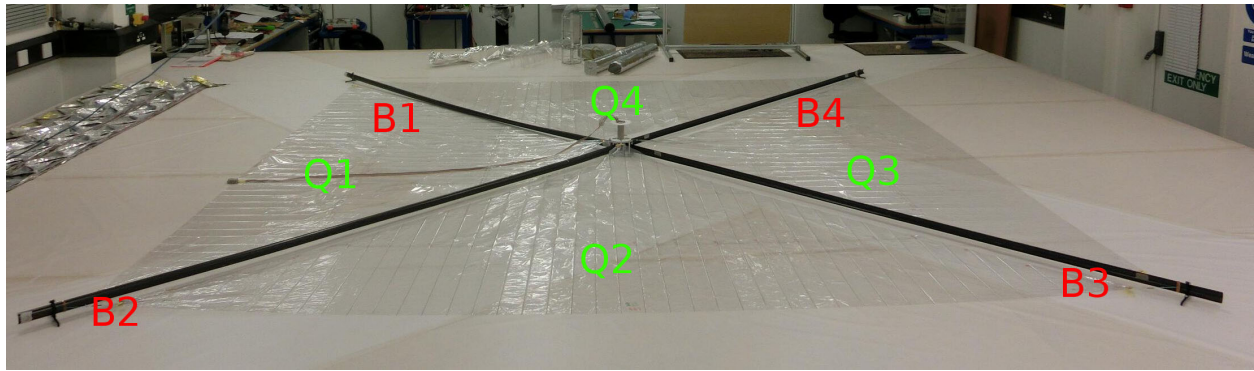


Figure 10. The InflateSail sail in fully deployed configuration.

## 2. Thermal Deployments

A series of sail deployments was performed in the SSC thermal chamber, to evaluate the performance at high/low temperature conditions ( $+60^{\circ}\text{C}$  and  $-25^{\circ}\text{C}$ ). For the tests the sail deployment module was instrumented with temperature sensors to ensure that the deployment motor had reached the desired temperature. The sail bundle was prevented from unfolding using a Dyneema string, which was cut using a burn wire before the boom deployment. In the flight model the sail bundle is restrained using rods attached to the boom tips. Due to size limitations of the thermal chamber only partial deployments could be performed, and these were all successful. The motor current was not recorded, but the maximum value was monitored on the power supply and this showed an increase for the low temperature deployments (approximately 0.3 A peak current for cold case, compared to 0.15 A for the hot case; this was for the EM 12V motor).

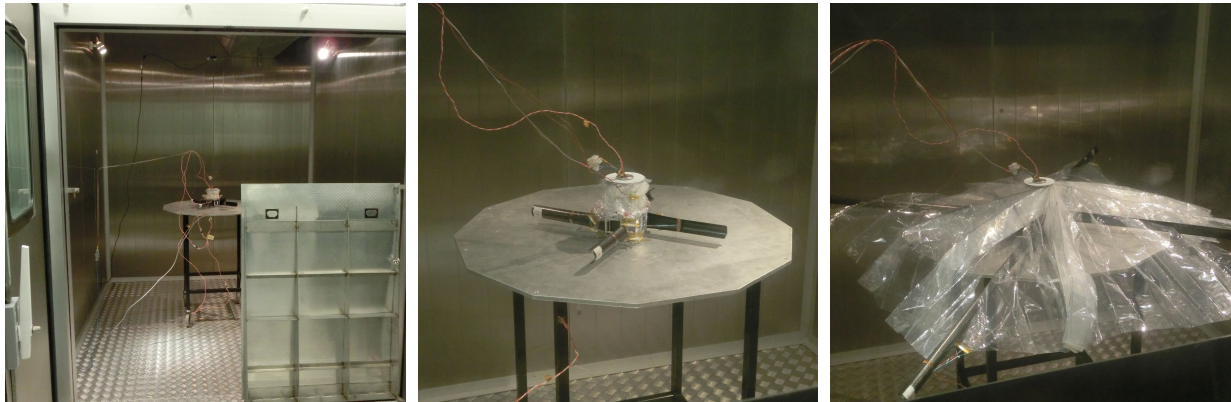


Figure 11. Sail deployments in the SSC thermal chamber.

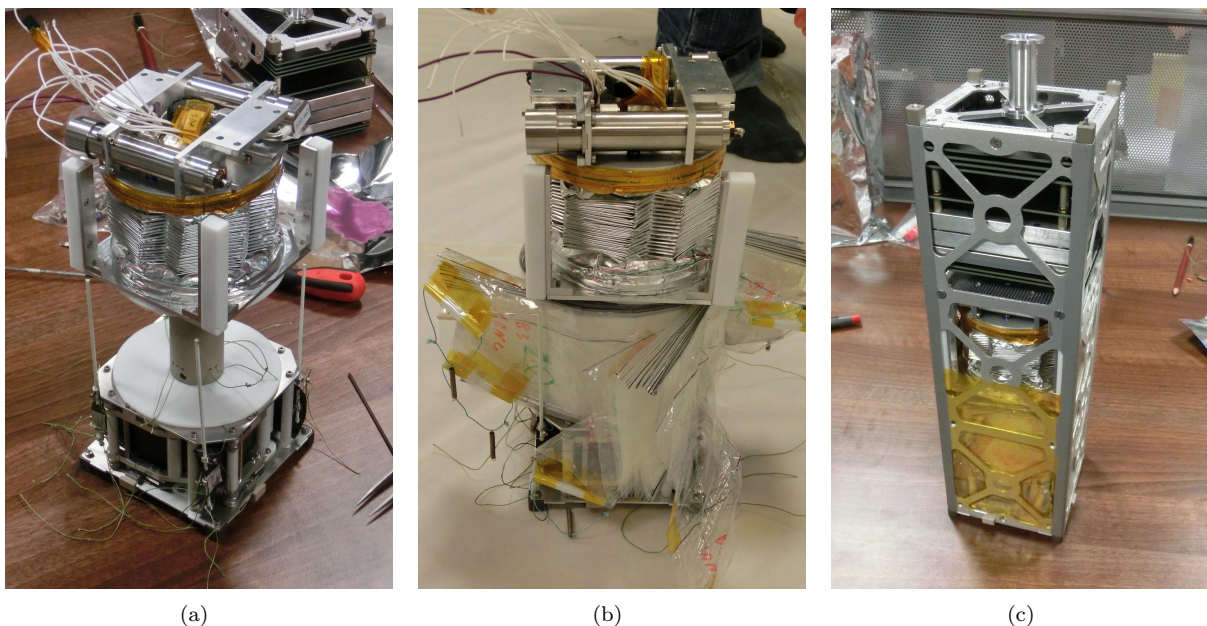
## IV. Qualification Testing

The qualification testing campaign consisted of an ascent-vent simulation, vibration testing, and thermal cycling. The assembly of the qualification model for vibration testing is shown in Figure 12. A motor identical to that used in the Flight Model (with Braycote vacuum grease) was installed. A QM CGG was installed, and the empty casing of the CGG fired during the vacuum deployment test described in Section III.A.3 was included as a mass dummy.

### A. Ascent Venting

The folded inflatable encloses a small volume of air which must be vented during launch. To this end a miniature normally-open solenoid valve (Lee LHDA0560365D) was fitted to the base of the inflatable.

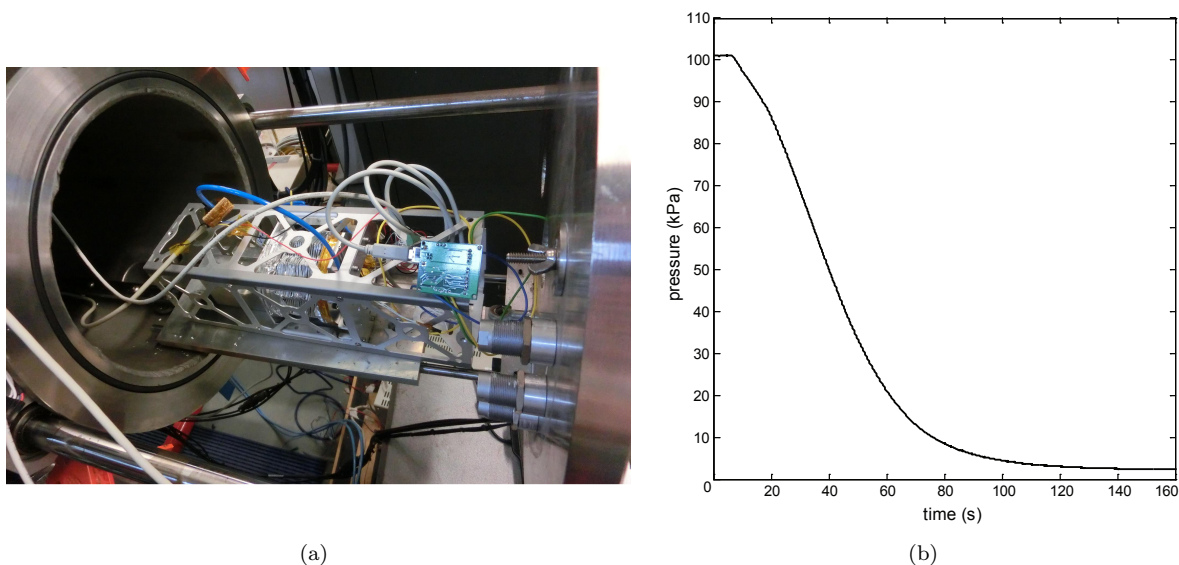




**Figure 12.** Assembly of structural qualification model for vibration test, with (a) the inflatable connected to the sail deployer, (b) sail wrapped around the storage spindle, and (c) the completed QM model with mass-dummies for the avionics.

During the inflation and rigidisation process the valve is temporarily closed.

To test the valve's ability to vent the air trapped in the inflatable during launch, a rapid decompression test was performed. A folded inflatable was installed in the structural test chassis, and placed in a small 'pod' attached to the side of a large volume vacuum chamber; see Figure 13(a). An absolute pressure sensor was installed inside the inflatable, and a differential pressure sensor was used to measure the pressure differential between the inside and outside of the folded inflatable. The small pod was sealed, before being vented to the main body of the chamber in a controlled manner over the course of 60-80 s.



**Figure 13.** Ascent vent testing, (a) the folded inflatable inside the test CubeSat chassis loaded into a small pod attached to a larger vacuum chamber, and (b) the absolute pressure inside the folded inflatable during the test; the pressure differential between the inflatable and the chamber remained below 0.2 kPa.

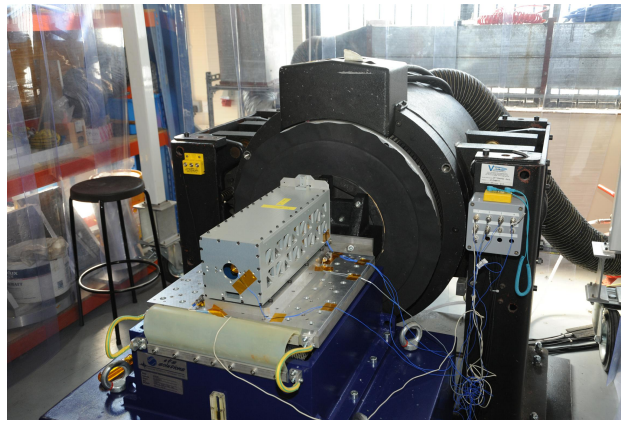


Figure 14. The structural qualification model undergoing vibration testing.

The results of one of the ascent vent tests are shown in Figure 13(b). The trace shown is taken from the absolute pressure sensor inside the folded inflatable. The differential pressure sensor did not record anything significantly above the noise floor of the sensor. No visible change in the folded inflatable was detected.

## B. Vibration Testing

The InflateSail structural qualification model was subjected to a series of vibration tests as part of the test campaign for the QB50 mission. This consisted of sine and random vibrations, and a quasi-static test. Low level sine sweeps were performed between each test to detect any changes in resonance. The test values in Tables 1–4 are adapted from the QB50 satellite specifications.<sup>10</sup> All axes were tested to the same levels due to uncertainty about the final orientation of the satellite within the launch vehicle. Accelerometers were placed on the top and bottom faces of the CubeSat structure, as well as on one of the side faces. One accelerometer was placed internally on top of the avionics mass dummy.

Table 1. Low level sine sweep

Frequency (Hz)	5 - 2000
Acceleration ( $\pm g$ )	0.5
Sweep rate (octaves/minute)	2
Sweep direction	one upwards sweep
Control strategy	average control

Table 2. Qualification sine levels

Sweep rate (octaves/minute)	2
Sweep direction	one upwards sweep
Control strategy	average control
Frequency (Hz)	Acceleration $\pm g$
5	1.2
8	2.5
100	2.5

The vibration tests showed no major structural resonances within the specified range of 0-90 Hz, and no significant shifts in resonances between each of the main acceleration and vibration sweeps.

## C. Thermal Cycling

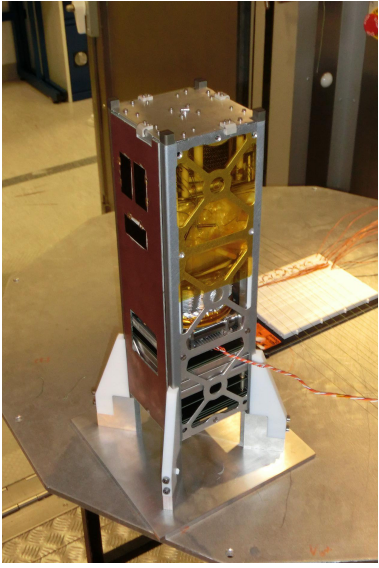
The qualification model was subjected to a single thermal cycle at atmospheric pressure. The purpose of this short test was to subject the motor and CGGs built into the structure to a final stress test before test firing the second qualification CGG, and checking the proper functioning of the motor and boom deployer unit. The cycle is shown in Figure 15(b).

Table 3. Qualification random vibration levels

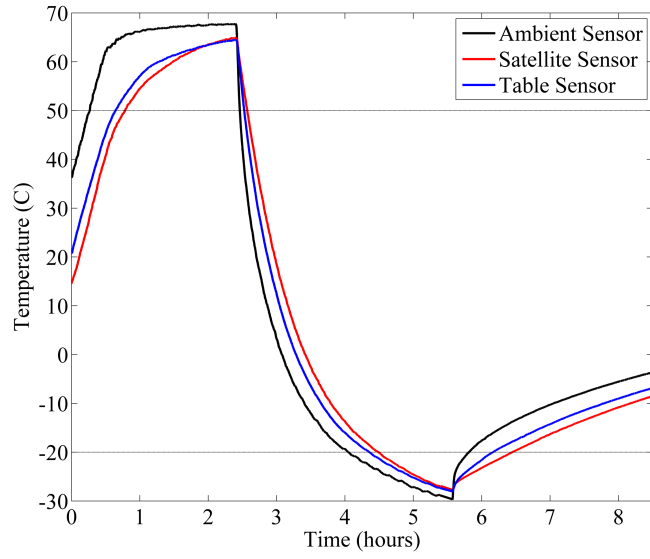
Duration per axis (s)	120
$g_{RMS}$	8.026
Control strategy	average control
Frequency (Hz)	PSD $g^2/Hz$
20	0.009
130	0.046
800	0.046
2000	0.015

Table 4. Qualification quasi-static acceleration levels (test carried out as short sine sweep)

Sweep rate (octaves/minute)	4
Sweep direction	one upwards sweep
Control strategy	average control
Frequency (Hz)	Acceleration $\pm g$
16	0.5
18	10.8
20	10.8
22	0.5



(a)



(b)

Figure 15. The InflateSail Qualification Model (a) inside the thermal chamber; (b) temperature trace for the thermal cycle.

#### D. Post-Qualification Functional Testing

Following the ascent-vent, vibration, and thermal cycling of the qualification model, two final functional tests were performed to ensure that the CGG and the sail deployment motor had survived.

In the first test, the CGG was fired in lab conditions at atmospheric pressure and room temperature. The CGG ignited successfully, and the expanding inflatable pushed the sail deployer out of the top of the chassis. This also represented a verification of the jack-in-the-box deployment technique. The inflatable only extended to approximately half of its full length because of the external atmospheric pressure.

The second test involved a simple table top test of the motor driven sail deployment unit. No anomalous behaviour was observed during this test, indicating that the motor and sail deployer had survived the qualification process.

## V. Conclusion

The InflateSail payloads have undergone a series of functional and qualification tests in preparation for their launch as part of the QB50 mission. The development programme has required the construction of separate engineering, qualification, and now flight models. The engineering model was used to verify the deployment method and to perform functional tests in various laboratory, thermal and vacuum conditions. The (structural) qualification model was used to perform vibration and thermal tests. The CGGs designed specifically for InflateSail have been tested both independently, and whilst integrated into the system. The flight model has been manufactured and assembled, and will undergo a series of acceptance tests including thermal vacuum, EMC, and acceptance-level vibration.

## VI. Acknowledgements

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